TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 642

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By Friedrich Seewald

Zietschrift für Flugtechnik und Motorluftschiffahrt
Vol. 22, No. 12, June 29, 1931
Verlag von R. Oldenbourg, München und Berlin

Washington
October, 1931

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For several years the problem of flutter in propeller blades has grown increasingly important, due to the increasing number of propeller breaks which could not be satisfactorily explained. Even after it was decided that the excessive stressing was produced by vibrations, this did not help much, so long as no means was found to prevent the vibrations. No general solution of this problem has yet been found. A beginning has been made, however, and I will now endeavor to set forth the present status of the problem.**

Since the phenomena of flutter in propeller blades have not hitherto been susceptible of accurate experimental determination, sufficient data are not yet available to determine the nature and still less the cause of the vibrations. All that can be done is to consider what kinds of vibration are possible and what causes might produce them. There are two fundamentally different possibilities, namely:

1. Combined vibrations of the blade, similar to those of wings, which develop by absorbing energy from the air stream and converting it into vibrations without the aid of any periodic external disturbance.

2. Forced vibrations, which are produced in every structure by periodically variable impulses. Such vibrations are especially dangerous, when the disturbing impulses, which cause them, have a frequency equal or nearly equal to the natural frequency of the system.

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*"Ueber die Schwingungserscheinungen an Luftschrauben." From Zeitschrift für Flugtechnik und Motorluftschiffahrt, June 29, 1931, pp. 369-374.

**An exhaustive presentation of some of the questions under consideration has already been published. See F. Liebers, "Resonanzschwingungen von Luftschrauben." 182 D.V.L. Report in Luftfahrtforschung, 1930, pp. 137-152, and D.V.L. (Deutsche Versuchsanstalt für Luftfahrt) Yearbook, 1930, pp. 79-94.

1. Combined Torsional and Bending Vibrations

We are of the opinion that the first-named kind of vibration does not affect propellers as now made, and I will briefly explain the reason. We will first refer to the result of an investigation by Birnbaum, which indicates that, in propeller-blade vibrations, energy is transferred from the air stream to the vibrations only when it has two degrees of freedom, torsional and bending. According to Birnbaum, neither a purely torsional nor a purely bending vibration can be increased by the aerodynamic forces, but combined vibrations having both torsional and bending components probably can be.

The nature of such combined vibrations in a wing has been explained in previous reports,* and is fundamentally as follows. When a wing, which is rigidly secured at one end, is subjected to impacts, a vibration in two components is usually developed, namely, that of bending, in which the individual profiles move perpendicularly to the wing chord, and torsion about the longitudinal axis. There are also bending vibrations in a plane approximately parallel to the lower side of the wing. In this plane the natural frequency of the wing is so great or (what amounts to the same thing) the wing is so rigid that the amplitude of this vibration is very small in comparison with the other components. The latter components will be disregarded at the outset. The other two components usually occur together. Even if only one component is present at first, it soon develops the other.

The fact that one vibration component develops the other is principally due to the effect of inertia. In order to illustrate this, we will imagine a wing so constructed that the spar or spars are replaced by a steel tube, on which the individual wing sections rotate without friction. In order to obtain torsional rigidity, imagine those sections connected with the tube by springs, so that when a section is rotated about the tube, a certain elastic moment is produced.

We will now imagine the mass of each section to be so distributed that its C.G. is in the axis of said tube. If bending vibrations are then imparted to the tube representing the spar, there will be no relative distortion of the

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*H. Blenk and F. Liebers, "Flügelschwingungen von freitragenden Eindeckern." 80th D.V.L. report in Luftfahrtforschung, 1928, pp. 1-17 and D.V.L. Yearbook, 1928, pp. 63-79.

individual sections, but they will share in the elastic vibration of the tube so as to move back and forth parallel to themselves.

Such is not the case, however, when the C.G. of the wing section lies outside the spar axis. Imagine the C.G. to be shifted toward the rear by hanging weights on the trailing edge. If the spar is then bent and suddenly released, the bending vibrations immediately set up torsional vibrations, since the elastic force of the spar does not then act on the C.G. of the section, but produces a torsional moment due to the lever arm between the C.G. and the spar axis.

If the vibration occurs in an air stream, it is affected by the aerodynamic forces, so that the angle of attack varies according to whether the wing moves up or down and also with the elastic distortion of the given section. This variation in the angle of attack affects the lift and the torsional moment of the aerodynamic forces.

If, due to the aerodynamic and inertia moments, the elastic distortion of the wing produces a smaller angle of attack during the downward motion than during the upward motion, it means that every time the wing moves upward the lift is increased and every time it moves downward the lift is decreased. The effect is just the same as if a force acted on the wing in consonance with the vibrations, thereby increasing their amplitude. Energy is thus permanently transmitted to the vibrations and their amplitude increases even though the original disturbance is only slight, until the wing breaks, or until the internal damping absorbs just as much energy as is added externally. Hence such a vibration is never possible when a wing has such a torsional rigidity that the aerodynamic and inertia moments can produce only slight torsional angles during the vibration.

In a propeller the masses are all near the elastic axis and have their C.G. practically in this axis, so that the force of inertia can exert no considerable moment. The chord of the propeller blade is very short, so that the aerodynamic force can act on a short lever arm and produce only a slight distortion. Only at very large angles of attack can the aerodynamic forces then develop torsional moments which produce important distortions. It is therefore obvious that the conditions for the production of such vibrations are not present to the same degree as in a wing, where the distortion is much greater, due to the long lever arms of the aerodynamic and inertia forces.

Even small forces and moments may produce vibrations of great amplitude when the vibrations have a frequency approximating the natural frequency. In a combined vibration this danger is diminished in proportion to the difference in the natural frequencies of the two component vibrations, torsional and bending. An experimental investigation of the rigidity of ordinary propeller blades shows that the natural frequency of the torsional vibrations is of another order of magnitude than that of the bending vibrations. The disturbing impulses resulting from the bending vibrations form, to a certain degree, a static load for the torsion, which changes slowly, so that the distortion is proportional to the effective moment. Since the torsional moments are small, no considerable distortion, which constitutes the preliminary condition for the development of combined vibrations, can occur.

Calculation shows that the torsional moments would have to be of an entirely different order of magnitude, in order to cause the variations in the angle of attack, which constitute the preliminary condition for dynamic instability. Either the aerodynamic forces and moments (i.e., the propeller r.p.m.) or the blade chord and, consequently, the lever arms of the aerodynamic and inertia forces would have to be considerably larger than is now the case, for such combined vibrations to occur in propellers of normal torsional and bending rigidity.

Although the mathematical solution of this problem is possible only under simplified assumptions, and hence the numerical results of such investigations must be accepted with caution, the data are, nevertheless, sufficiently accurate, since they concern only an approximation of the order of magnitude.

2. Vibrations with One Degree of Freedom at Large Angles of Attack

This condition obtains only when the propeller blades are functioning at a normal angle of attack and hence considerably below the angle of maximum lift or thrust. When the lift on individual sections approaches the maximum, other conditions are introduced. For example, it is obvious that simple bending vibrations, not combined with any other component, are possible in this case. When the angle of maximum lift is exceeded, the lift and the normal force decrease as the angle of attack increases. When the blade is moving downward, an additional negative lift is generated, a force which exerts an accelerating effect on the motion. A corresponding effect is produced by the upward motion. Hence the bending vibrations are accelerated by the aerodynamic forces beyond the angle of maximum lift.

The often-expressed opinion, that such vibrations actually occur in propeller blades, is strengthened by the fact that there are propellers which run smoothly up to certain angles of attack and then suddenly begin to flutter on the least further increase. This explanation must, however, be somewhat amplified, in order to bring it into harmony with experience.

If it is assumed that the maximum lift is exceeded by increasing the pitch, we then have the conditions for a self-amplifying vibration at any speed. It would therefore be assumed that the vibrations begin with small amplitudes at low revolution speeds and continually increase in amplitude as the revolution speed increases. Such is not the case, however, according to my observations. Up to a certain revolution speed, the propeller runs just as smoothly at the greater pitch as at the smaller. Above this speed violent vibrations set in. With further increases in the revolution speed, the vibrations often grow no stronger, and if the revolution speed is again reduced, the vibrations disappear at somewhat lower revolution speeds than those at which they were first produced. This seems to indicate forced vibrations.

If the aerodynamic measurements in static wing tests could be transferred to this problem, it would also have to be assumed that the maximum lift was considerably exceeded, so that such vibrations could occur, since the aerodynamic force and moment vary but slightly in the vicinity of the maximum lift. Here the conditions of vibration are approximately the same as if the propeller were running in a vacuum. In this field, however, there is considerable uncertainty regarding such considerations. Here the effect of the position and state of motion of the blade is still greater than at small angles of attack. Probably the aerodynamic force and its moment will behave otherwise than static tests would lead one to expect. It is known that in this field it makes a difference from which direction a given angle of attack is approached.

A mathematical determination of the lift and moment in terms of the state of motion is hardly feasible at large angles of attack. The only available resource is the theory of vortex surfaces. This is applicable, however, only when a small region outside the wing section (the boundary layer) is affected by the friction, while a potential flow prevails beyond this region. This condition no longer exists at large angles of attack. It is possible that, in the field of large angles of attack, the variations in the lift and in the aerodynamic moment, caused by the oscillation of a blade, may be such that vibrations, however started, can be further amplified by the aerodynamic forces.

The whole question is closely connected with the phenomenon of vortex separation and, in so far as it concerns the torsional vibration, a direct resonance is conceivable between vortex separation and blade vibration. In the inner portion of the propeller disk (up to about half its radius), where the angle of attack of a propeller blade with a high pitch, especially when running on the stand, is very large (of the order of magnitude of 45°) and where the flow definitely separates, a vortex trail must be formed, whose width is of the order of magnitude of the blade chord. A mathematical estimation, according to Karman's researches on vortex trails, shows that for ordinary propeller blades and revolution speeds, the frequency of the vortex separation in this inner portion of the blade is of the same order of magnitude as that of the torsional vibration.

On the rest of the propeller, where the flow, even at high pitches, has not yet separated, the frequency of the vortex separations is considerably greater than the natural frequency of the propeller blades. Since, however, even this part of the propeller functions with relatively large angles of attack at a high pitch, the damping by the aerodynamic forces is here very slight. It is possible that, even under these circumstances, the energy of the vortices may suffice to maintain vibrations of finite amplitude.

Hardly more than surmises can be made, however, regarding the vibration phenomena connected with the angle of attack. In order to solve these problems, it will be necessary to investigate flows in which the sections are moved similarly to what they are in actual vibrations.

3. Effect of Curvature

In the preceding discussion it has been assumed that the blade axis is straight, for only then is there any sense in designating the vibration components as bending and torsional. If the propeller blade and its axis (the line passing through the C.G. of each blade section) are curved, as is generally true in practice, such is no longer the case. The terms bending and distortion apply, for a curved blade, only to a cross section or to a section of the blade which is so short in the direction of the axis that it may be considered straight. The torsion of any other section produces not only a distortion about its longitudinal axis, but also a displacement which is essnetially parallel, corresponding to the bending. Moreover, a propeller blade is always twisted, so that the principal axis of inertia has a different direction in every cross section. Even with static loading, the mathematical computation of these influences is troublesome, and the investigation of the vibration phenomena is very difficult. I will say a few words regarding only one case of practical interest, so far as it is possible to gain an insight without calculation. Imagine a propeller blade having a pronounced rake, as was formerly often the case. The rake is somewhat exaggerated in Figure 1.

If only the blade sections near the hub are regarded as elastic and the rest of the blade as rigid, then the rake increases the inertia moment of the elastic sections about the axis of torsion and therefore reduces the torsional frequency. The frequency of the bending vibrations also varies according to the torsional weakness of the blade, because the outer portion of the blade, which was temporarily assumed to be rigid, with every elastic yielding of the inner portions simultaneously distorts the latter. Due to this distortion, the outer portions do not have the same amplitude as in a straight blade, which would likewise make a bending oscillation about the elastic portion near the hub. Hence the mass would have to be reduced. The frequency of the bending vibrations would thus be increased.

In an actual investigation of the problem, all the sections must, of course, be regarded as elastic, and the relations are extremely complicated with respect to any given camber. It is already recognized, however, that both frequencies approach each other, whereby the higher frequency is reduced, thus favoring instability. The often-expressed opinion that the rake of the blade tips improves the stability is, therefore, not absolutely correct. Perhaps the opposite conclusion would come nearer the truth.

In most present-day propellers the axis more closely approaches a straight line. I would, therefore, like to assume that the effect of the camber necessitates a slight correction of the results, but makes no important change in the general principles. The possibility of a condition, which is dynamically unstable due to the simultaneous action of aerodynamic forces and elastic inertia forces, cannot be definitely denied, however, until cambered propellers have also been investigated.

The terms torsional and bending vibrations will also be used in what follows, even though not strictly applicable to all shapes of propellers. They are plausible, however, in spite of this consideration. It is only necessary to visualize, on the one hand, the vibrations for which the distortion of the profiles is great in comparison with the other deformations and, on the other hand, the vibrations for which the distortion of the profiles is small in comparison with the parallel displacements of the cross sections. These forms of vibration can be visualized as experimentally produced by imparting a vibration with a regular frequency to an unbalanced rotating disk. At a certain rotational speed of the unbalanced disk, the propeller blade suddenly makes large deviations, for which the component, which is essentially perpendicular to the pressure side of the blade, overbalances all other deformations. This is designated above as the bending component. In a nonrotating conventional propeller, this vibration occurs at about 25 to 40 Hertz.

If the rotational speed, and consequently the frequency of the impulses, is further increased, this vibration disappears, and strong deflections are generally produced at 150 Hertz and above, due to resonance with another form of vibration, which causes large angular variations in all the sections. If we designate these two components as torsion and bending and introduce the frequencies of both forms of vibration as experimentally obtained in the above manner, allowance is thus made for the bending of the axis, in so far as the elastic properties are affected.

4. Forced Vibrations

It now remains to investigate the second form of vibrations, which are produced by some periodic external disturbance and which are generally called forced vibrations. Since the deflections and stresses in such vibrations are particularly large and dangerous when the period of excitation is in resonance with the natural vibration, they are called resonance vibrations. For aircraft propellers the disturbing factors are:

1. Variations in the engine speed;

2. Separation of vortices from the propeller blades, producing periodic fluctuations in the aerodynamic forces;

3. Periodically varying impact of the blades, due to lack of uniformity of the field of flow in the plane of the propeller disk.

The possibility of setting up vibrations by the separation of vortices has already been discussed, so far as is possible with our still very imperfect knowledge. The last of the above causes appears to be the most important, since the periodically varying forces and moments, produced by the irregular impacts, are much larger than those produced by the other disturbances.

For this kind of vibrations, the task is first to determine the different natural frequencies peculiar to a given or projected propeller. The main difficulty consists in the complexity of the propeller blade. The solution of even the simplest case is very difficult for a blade with a variable cross section. Moreover, the natural frequency is changed by the centrifugal force which, in the case of a bend, tends to straighten the blade. The centrifugal force therefore tends to diminish the natural frequency.

A method for determining the natural frequency of aircraft propeller blades is discussed in the above-mentioned report of Liebers, at first with limitation to a straight propeller axis. His solution confines the natural frequency between an upper and a lower limit. Since these limits are very near together, the natural frequency is thus very accurately obtained, while avoiding the mathematical difficulties of a direct solution.

In determining the upper limit, use is made of a principle of Rayleigh, which reads as follows: Of all the possible deformations of a vibrating system, that one is actually produced which yields the minimum frequency. If we adopt, for example, in the investigation of the bending vibrations of a bar, any lines of bend compatible with the marginal conditions and calculate the natural frequency for each line (whereby, in our case, the centrifugal force must naturally be taken into consideration), the actual line of bend is most closely approximated by that one of the assumed lines of bend which has the lowest natural frequency. Even for this line, however, the natural frequency will generally be too high, unless the correct line of bend has been accidentally adopted. The deviations are small, however, since the minimum natural frequency varies only by small amounts when the line of bend undergoes slight changes.

Hence, if the adopted lines of bend are only approximately correct, a close approximation is nevertheless obtained for the natural frequency. This approximation, which can yield only excessive values, can be easily calculated for a bar with any series of cross sections. For the bending frequencies of ordinary propeller blades, this is done in the above-mentioned report with the aid of two characteristic parameters of the shape of the blade.

A method for determining the lower limit of the natural frequency is detailed in Liebers' report. Only the fundamentals of this method will be briefly given here, with reference to the following theorem first demonstrated by Southwell. The square of the natural frequency of an elastic system, subjected to several forces, is always greater than the sum of the squares of the frequencies, which the system would have, if only one of these forces were acting at a time. (Lamb and Southwell, Proc. Roy. Soc., Vol. 99, London, 1921.) An aircraft propeller blade is first subjected to the elastic forces. Only these are present when the propeller is not running. The resulting frequency is easy to determine experimentally, by subjecting the propeller to impacts and recording and counting the vibrations. This frequency is designated by λ_0. If we now imagine the elastic forces removed, so that we have, as it were, a flexible chain or rope of corresponding mass, we then have only the centrifugal force remaining. It is easily demonstrated that such a system has bending vibrations with a frequency equal to the angular velocity ω.

For the true frequency λ under the action of both forces we then have

$$\lambda > \sqrt{\lambda_0^2 + \omega^2}.$$

(By frequency is here meant the so-called circular frequency, or 2π times the number of vibrations per second.) With the addition of a constant for taking into account the shape of the blade, this inequality, which yields the lower limit, has already been suggested as an approximate solution for the true frequency. (Southwell and Gough, "On the Free Transverse Vibrations of Airscrew Blades." British A.R.C. Reports and Memoranda No. 766, 1921.) Comparison with the above-determined upper limit shows that the complete consideration of the shape of the wing and of the line of bend (which varies with the revolution speed) considerably diminishes the distance between the upper and lower limit. The inequality then takes the form

$$\lambda > \sqrt{X_1 \lambda_0^2 + X_2 \omega^2},$$

in which X_1 and X_2 are functions which contain the characteristic parameter of the wing shape and which can be calculated once for all for any given shape on the basis of the general law. The details are given in the already frequently mentioned report of Liebers.

If it is also found that the thus calculated natural frequency is not greatly affected by the aerodynamic forces and an after calculation yields, in fact, this result for the usual present-day types, the first part of the problem is solved, at least for one degree of freedom, namely, the determination of the vibrational characteristics of a revolving propeller blade. The vibration number of this component, for a nonrotating propeller, is generally $X_1 \nu_0 = 25 - 40/s$, and increases according to the formula

$$\nu = \sqrt{X_1 \nu_0^2 + X_2 n^2}$$

in which n denotes the number of revolutions per second.

In like manner calculations could also be made for the torsional vibrations. Since we know in advance, however, that the effect of the centrifugal force is small on torsional frequencies of the higher order, we can assume that the torsional frequency, determined experimentally with the propeller at rest, closely approximates that of the revolving propeller. The frequency of the torsional is generally 150 Hertz or more.

The most disagreeable of these components is the bending (on the stand) with the low frequencies of 25 to 40 s, which are therefore of the same order of magnitude as the torsional frequencies. The condition for resonance often occurs when there are two disturbances during every revolution. As the revolution speed increases, the effect of the contrifugal force is to increase the natural frequency of this vibration. In Figure 2, the natural frequency is plotted against the revolution speed for two examples: I, a relatively thin metal propeller; II, a still more yielding propeller model.

Increasing the natural frequency has the advantage of increasing the revolution speed at which resonance occurs. No resonance can be produced by any disturbance of the same frequency as the revolution speed, if the propeller has a certain rigidity and no joints. It will be seen, however, that in the chosen example, any disturbance, occurring twice during a revolution, comes into resonance with the bending vibration at relatively low revolution speeds. The double disturbance per revolution, however, occurs quite frequently, e.g., when a propeller revolves, either before or behind the wing, so that each blade passes by the wing twice per revolution. Moreover, it is known that the resonance region is widened by the increase in the natural frequency of the centrifugal force, since if the "supercritical" region is reached by increasing the revolution speed, the natural frequency also increases, though not in the same degree.

5. Apparatus for Observing the Vibrations

A rotating prism or rotoscope P (fig. 3) is mounted in front of the propeller with its rotational axis in the same straight line as the rotational axis of the propeller. This prism is driven by a motor M synchronized with the propeller shaft. The rotation of the propeller is eliminated for the observer by the rotation of the prism. To a person looking through the rotoscope, the propeller appears stationary and perpendicular to the surface of the propeller disk. Not much can be accomplished in this way, for the most important deformations (bending vibrations perpendicular to the propeller disk and torsional vibrations) produce motions of the blade in the direction of observation and hence difficult to recognize. This difficulty can be overcome by mounting a mirror S (fig. 3) on the propeller shaft in such a way that it shows the observer looking through the rotoscope, the image of the propeller as it would appear if he were looking along the blade from the shaft. The rotoscope is so located, with lenses in front of it or at a suitable distance, that one observes only the mirror. If several cross sections are marked by a white line, the deformations undergone by these cross sections can then be observed. Since the vibrations are generally much too rapid for observation with the naked eye, they are recorded by a special rapid motion-picture camera. This method proved very successful, though there was difficulty in obtaining a strong enough light. With the aid of the D.V.L. photographic section, however, this difficulty was so far overcome that it gave satisfactory results with the rather slow propellers used.

6. Resonance between the Disturbing Impulses and the Bending Vibrations

This arrangement serves to show whether the above method for calculating the natural frequency agrees with the facts. For this purpose a propeller was made with a cross-sectional and inertia moment as simple as possible for purposes of calculation. The experiments show that the calculation of the natural frequency of rotating blades agrees excellently with the experimental results. They show, moreover, that when the disturbing impulses are in resonance with the natural frequency, vibrations of large amplitude result, which fact hardly needs confirmation, however, if the determination of the natural frequency is found to be correct.

It has therefore been satisfactorily demonstrated that this is a possible kind of vibration which probably plays an important role in practice. In the practical application of these results, it might often be quite difficult to obtain just the right degree of rigidity to avoid the danger of resonance. Since, in addition to the variations in the flow with one or two impulses per revolution, there are also disturbances due to the engine, the working stroke of a six-cylinder four-stroke engine, e.g., gives three impulses. According to the construction of the airplane, we often have to reckon with still other vibrational frequencies due to the disturbance of the air stream by the struts, etc.

7. Resonance between Disturbances and Torsion

There are often still other vibrations which cannot be explained as bending vibrations, and this furnishes the reason for investigating the possibility of torsional vibrations. In consideration of the fact that the natural frequency of these vibrations is so high as to be a multiple of 6 to 15 times the rotational speed, we are tempted to assume that no resonance occurs, since no such disturbance is probable. Even such high frequencies occur, however, for example, in the after one of tandem propellers. If this propeller revolves in the direction opposite to that of the forward propeller, as is customary, and has the same r.p.m., the after propeller encounters, during each revolution, twice as many vortex layers as the forward propeller, i.e., 8 per revolution with a four-blade propeller. Thus a field is entered which must lie far beyond the critical period for the bending vibrations, but which has a possibility of resonance for torsional vibrations. Perhaps this is why such pusher propellers afford special difficulties. In the field of large angles of attack, there are still other possibilities connected with the phenomena of vortex formation.

8. Another Possibility of Torsional Vibrations

There is another possible way in which large amplitudes can be imparted to high-frequency vibrations. In the impulses acting on an aircraft propeller, we are not dealing with forces and moments which have a simple harmonic course like that of a simple sine function of the time. In a few cases the impulses may have such a course, e.g., a propeller above the wing, as disturbed by the circulation about the wing. In other cases, however, we have to deal with brief, impulsive effects; for example, when the propeller blade passes through the boundary layer of the wing or close to the front of a landing-gear strut or test stand. In such a case, the same phenomenon as in resonance, namely, a continual increase in the amplitude, always occurs where the natural frequency is any integral multiple of the impulse frequency. The case is similar to that of a swing which is given a push at every second or third swing. Disregarding the damping, continually increasing amplitudes can thus be produced, since energy is imparted to the vibrating system at every second or third vibration and none taken away.

Moreover, it is obvious that a brief impulsive disturbance can even then produce large amplitudes, although this condition is not fulfilled, if the impulse is strong enough. The propeller is then struck and continues to vibrate until it receives another impulse. It appears that both these cases occur in practice and produce excessive stresses in aircraft propellers.

If this surmise is correct, the whole problem is thus shifted in the direction that, on the one hand, the disturbing impulses must be investigated with respect to their temporal course and the magnitude of the forces and moments produced by the disturbing impulses. On the other hand, it would be necessary to determine for the blade itself the inner damping, as likewise the amount of energy the airplane is capable of absorbing. Next to the desirable investigation of the effect of the camber on the vibration characteristics, these questions are the most important.

9. Summary

In conclusion it may be said that a few phenomena of this kind have been satisfactorily explained and that sufficiently simple and reliable criteria can be given for avoiding certain kinds of vibration. With increasing knowledge, however, the whole problem becomes more difficult and comprehensive. In order to solve the practically important cases within the near future, investigation must be restricted to definite phenomena. After a general idea of the problem has been gained, the most important task seems to consist in the further development of the experimental investigation methods, in order to be able to determine, for propellers which have shown vibrations, the nature and causes of the vibrations. Only in this way does it seem possible to gain an insight into the problems concerning which we can now only resort to surmises.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

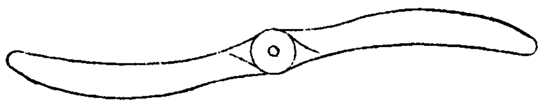


Fig. 1, Propeller with rake

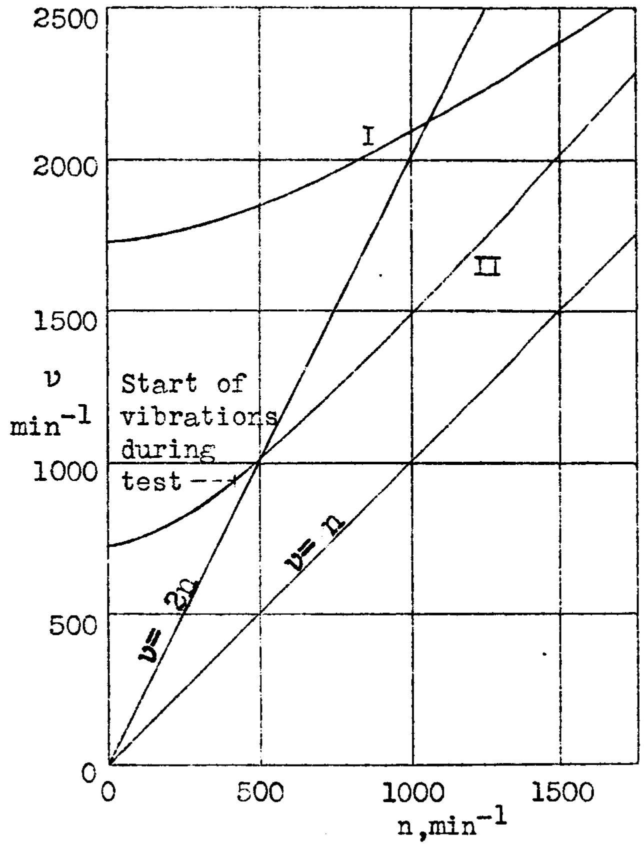
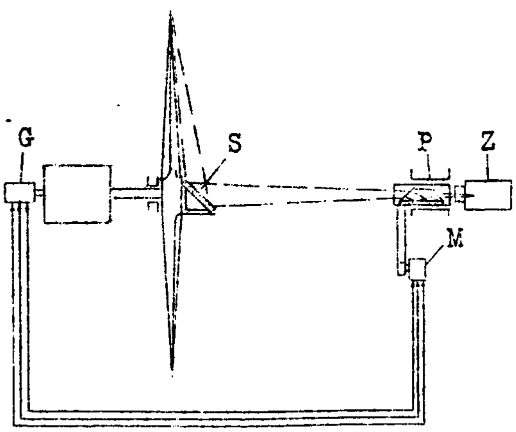


Fig. 2, I, bending frequency of a thin metal propeller; II, resonance at about 1100 r.p.m. for impulses of twice that frequency.



S, mirror
P, rotating prism or rotoscope
Z, camera
G, alternating-current generator
M, motor for driving rotoscope

Fig. 3, Apparatus for observing vibrations of aircraft propeller blades.